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GEOCHEMISTRY

New Data on Trace Element Distribution in Cassiterite from Tin Deposits of the Russian Far East

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The Sikhote Alin accretionary fold system of the Russian Far East incorporates a series of polymineral tin and tungsten deposits that were formed in different geodynamic environments of an active continental paleomargin. The Jurassic–Paleogene evolution of the Far East district was marked by the alternation of the suprasubduction (Andean type) and the transform-shift (Californian type) tectogenesis, which is related to changes in magmatism that promoted the formation of the majority of well-known large tin and tungsten deposits [1].

The analysis of geological data shows that the localization of polygenetic deposits is governed by their relation to continental paleomargin structures with the alternation of subduction and transform environments, which led to the formation of polygenetic mineralization. Geochemical and isotopic data indicate that the sources of the granite magmatism and ore-bearing fluids within this district are heterogeneous. On the one hand, they are associated with the subduction environment and, on the other hand, with the uplifting of asthenosphere diapirs through slab windows. This provides reason enough to presume that ore-magmatic systems have a complicated multistage structure which determined the multistage character of ore formation.

During the Jurassic–Paleogene geodynamic evolution of Asian continental margins, the southern Far East underwent the following stages of tectogenesis: (1) Jurassic–Early Cretaceous, 180–140 Ma (suprasubduction margin); (2) Early Cretaceous–Early Cenomanian, 140–93 Ma (transform margin); (3) Late Cenomanian–Paleocene, 93–55 Ma (suprasubduction margin); and (4) Eocene–Oligocene, 55–23 Ma (transform margin).

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Tin deposits of the Komsomol'sk district are located within the Khingan–Okhotsk metallogenic belt that was formed at the transform margin. Some age data show the completion of magmatism in the Khingan–Okhotsk belt after the Cenomanian simultaneously with suprasubduction magmatism in the Eastern Sikhote Alin belt. In the Kavalerovo district, tin-bearing magmatism is noted within the interval 105–45 Ma and is related to the geodynamic regimes of the transform, suprasubduction, and transform margin again (Fig. 1).

According to a new geodynamic model of ore deposits [2], tin deposits of the Russian Far East were formed under different geodynamic regimes, during which the geodynamic environment changed from the transform continental margin of the Californian type to the active continental margin of the Andean type and back to the transform margin again. To validate this model, we carried out a study of geochemical associations in cassiterite from tin deposits using a novel methodological approach that is based on the Aitchison geometry [3]. As was established earlier, a statistical analysis of geochemical mineral associations showed that mineral trace elements are conditioned by different factors, such as the deep crust structure, the magmatism type that the ore mineralization is associated with, and the genetic type of the deposits. Geochemical associations in minerals formed in the sialic basement are characterized by lithophile composition, but siderophile trace elements predominate in minerals from deposits that are associated with granite potassic series of higher basicity, which is typical for zones intermediate from an ocean to a continent [4]. As was established by multivariate statistics methods, geochemical associations in cassiterite are reliable criteria of genetic type and mineralization productivity [5].

To reveal indicator cassiterite properties that characterize ore-magmatic system evolution, we performed a comparative study of the geochemical features of cassiterites from tin deposits of the Primor'e and Amur regions. We studied the Festival'noe and Pereval'noe tin deposits of the Komsomol'sk district, which is located within the Khingan–Okhotsk metallogenic belt, and the large deposits of the Kavalerovo district from the Primor'e region, which is located within the Sikhote Alin fold system. The geochemical database used in this study includes the compositions of about 1000 samples of cassiterites, in which In, Sc, W, Nb, V, Cr, Be, Ti, Zr, Fe, and Mn were analyzed by the quantitative spectral analysis. We studied deposits of the Komsomol'sk district (Festival'noe and Pereval'noe), some ore zones (Kulisnaya, Tektonicheskaya, and Vostochnaya 8) from the Vysokogorsk deposit, and various zones from the Arsen'evsk deposit (Yuzhnaya, Induktsionnaya, Fel'zitovaya, Turmalinovaya, and Podruzhka), which are assumed to be formed under different geodynamic settings. To reveal the effect of the geodynamic regime on the ore formation, the discrimination between the tin deposits was done using a mathematical approach specially designed to analyze compositions.

The methodology is a combination of classical cluster and discriminant analysis with the Aitchison geometry of the simplex [6]. The key idea is to take into account the Euclidian vector space structure of available data and to work in coordinates with respect to an orthonormal basis [7]. The advantage of this method over classical statistical ones is its geometric presentation of the data.

In our case, the sample space is 12-part simplex (S12), the algebraic-geometric structure of which is summarized in [8]. The procedure may be characterized in the following way: (1) compositional observations are expressed in terms of coordinates in an orthonormal basis of the simplex; these coordinates are log ratios of components; (2) the desired statistical analysis is applied directly to the coordinates; and (3) the statistical results are interpreted in the simplex by applying them to the basis that was used.

With the aim of testing differences among deposits, this general procedure has been applied to a sample of cassiterite trace elements using a graphical representation based on a singular value decomposition, called a bi-plot [9], a Ward cluster analysis, and a hierarchical binary discriminant analysis that is based on the Fisher rule. The bi-plot explains 68% of the total variability and allows us to select a ternary (In, Nb, V) diagram, in which the data set presentation reproduces most of the variability inherent to the data. The Ward cluster analysis using the squared Aitchison distance as a dissimilarity criterion splits the total sample into four groups that correspond to some of the studied zones. The first group is identified with the Vysokogorsk deposit, Fel'zitovaya zone (Arsen'evsk deposit), and Pereval'noe deposit (Komsomol'sk district). The second group includes the latitudinal Turmalinovaya and Podruzhka zones of the Arsen'evsk deposit and the Festival'noe deposit of the Komsomol'sk district. The third and the fourth groups are subgroups that correspond to the Yuzhnaya and Induktsionnaya zones of the Arsen'evsk deposit. Figure 2 shows the spatial distribution of all the cassiterite samples corresponding to various zones of the studied deposits. The distribution pattern of cassiterites testifies to the contrast discrimination of trends in different parts of the space sample corresponding to two types of geodynamic settings that are related to the distinction in trace element composition.

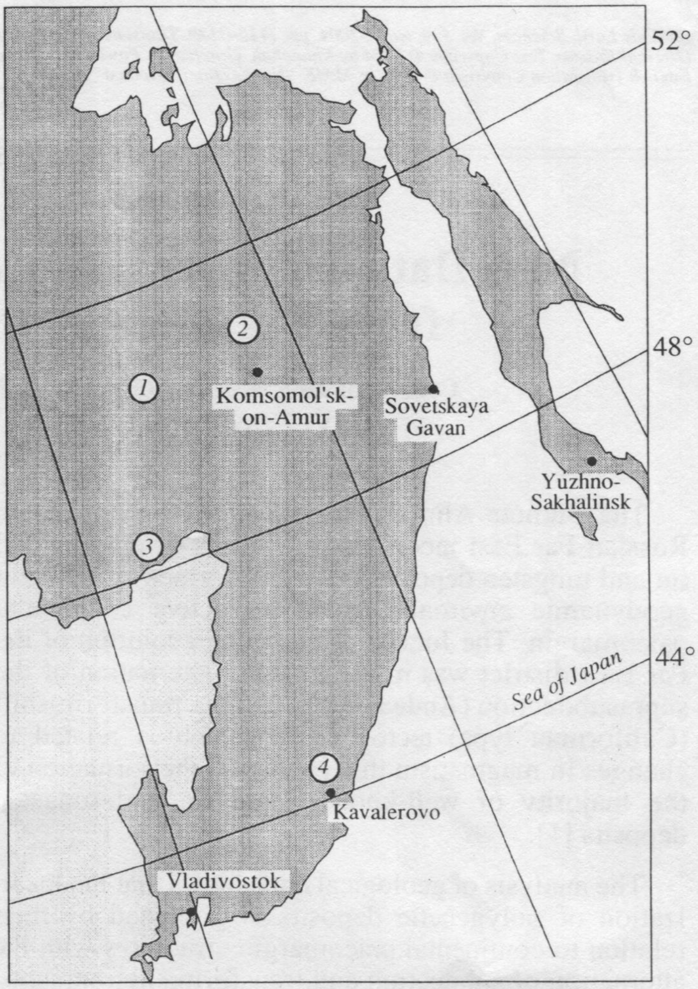

Fig. 1. Location map and ore districts of the Russian Far East. Ore districts: (*1*) Badzhal; (*2*) Komsomol'sk; (*3*) Khingan; (*4*) Kavalerovo.

Misclassification rates based on the rules obtained among these groups are below 3%. The correlation of discriminators with log ratios yielded the following functions: $f_1 = 1.72\ln(\text{InTiFe}/\text{Sc} \cdot \text{V} \cdot \text{Rst}) - 2.0$, which has positive values only in group 4 and negative values in the rest of the groups; $f_2 = 0.74\ln(\text{V}/\text{Nb}) + 0.275$, which is characterized by negative values in group 2 and positive ones in the other two groups; and $f_3 = (3.13 - 0.99)\ln(\text{Sc}/\text{Zr})$, which has negative values in group 1 and positive values in group 3. Thus, discriminant rules permit us to clearly separate the identified groups of deposits using the functions obtained (Fig.2).

The results obtained show that the tin deposits are grouped according to geodynamic settings (Figs. 3, 4).

The plots show a clear difference between groups 1–2 (transform margin) and groups 3–4 (active margin). The bi-plot and ternary diagram show trends of the deposits of the Komsomol'sk district and the Vysokogorsk deposit versus the Arsen'evsk deposit,

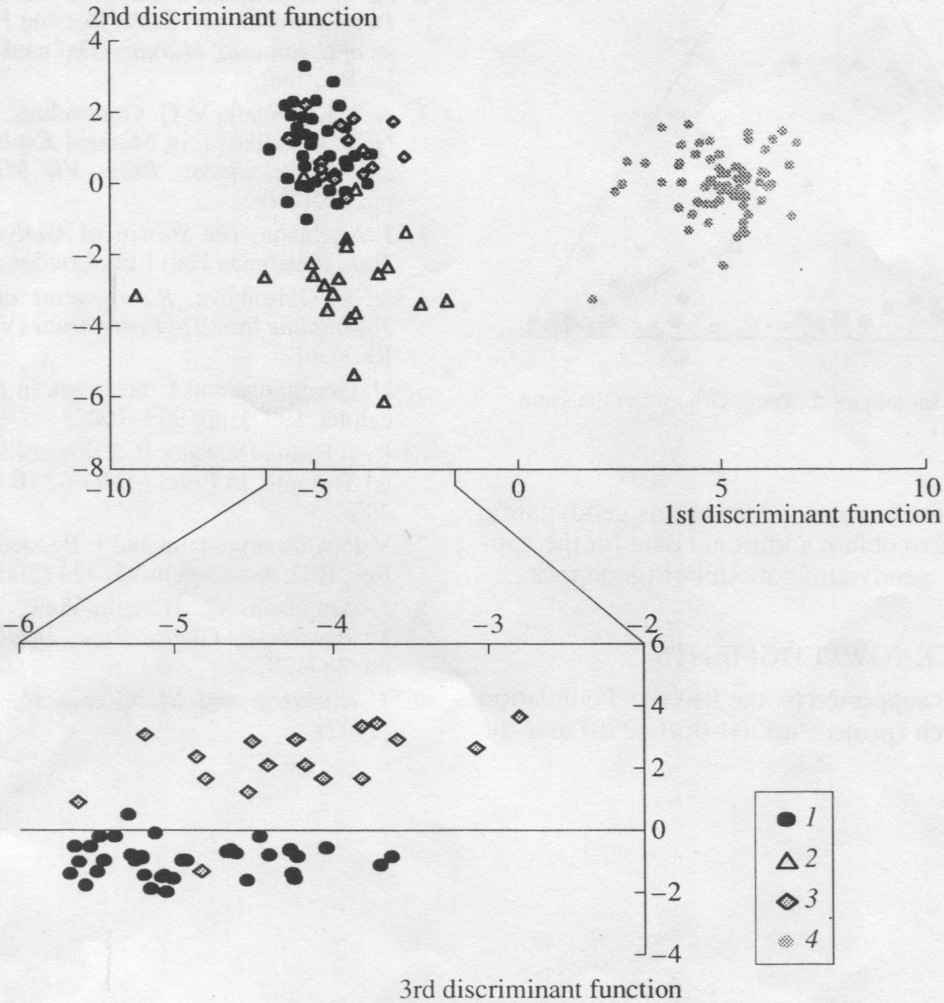

Fig. 2. Scatterplot of discriminant log-contrasts. (Group 1) Vysokogorsk and Pereval'noe deposits and the Fel'zitovaya zone; (Group 2) Turmalinovaya and Podruzhka zones (Festival'noe deposit); (Group 3) Yuzhnaya zone; (Group 4) Induktsionnaya zone.

Fig. 3. Bi-plot of trace elements in cassiterite compositions. Groups are the same as in Fig. 2.

excluding latitudinal zones. Similarly to the zones of the Komsomol'sk district and the Vysokogorsk deposit, these zones are formed under the transform regime. The Turmalinovaya and Podruzhka deposits are similar to deposits of the Komsomol'sk district and the Vysokogorsk deposit, although they have some distinctive properties. Therefore, it is inferred that the geodynamic environment significantly influences ore-magmatic system formation, a fact which is reflected in the mineral composition.

Thus, tin deposits of the Russian Far East can be classified into two main groups, which correspond to the most likely geodynamic settings: the early Cretaceous group (the Komsomol'sk district and the latitudinal zones of the Arsen'evsk deposit) and the late Eocene transform margin (typical of the Vysokogorsk deposit), and an active continental margin where submeridional zones of the Arsen'evsk deposit are formed. The results obtained clearly indicate that the revealed geochemical differences in ore association composition are conditioned by the features of the fluid regime, which is ultimately defined by geodynamic conditions. The geochemical differences revealed could be used to

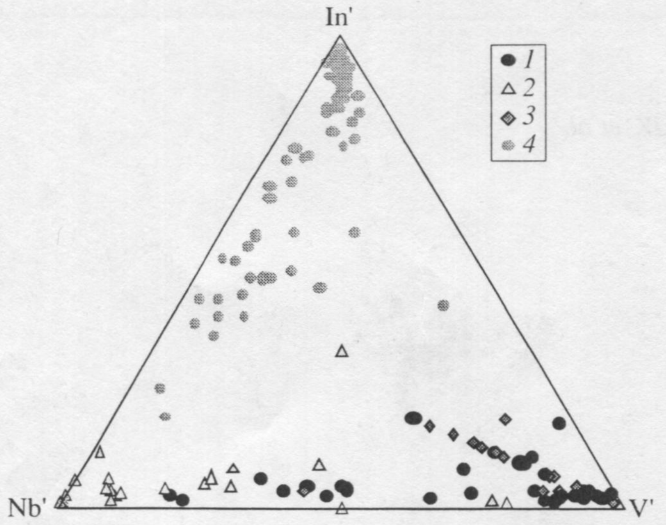

Fig. 4. Most-variant ternary diagram. Groups are the same as in Fig. 2.

identify tin deposits formed under various geodynamic environments and to obtain additional data for the validation of the new geodynamic model of tin deposits.

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